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Author: D. L. Broder, K. K. Popkov and S. M. Rubanov

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CHAPTER XII

ASSURING RADIATION SAFETY ABOARD ATOMIC-POWERED SHIPS

62. Sources of Radiation From A Marine Reactor.

Penetrating radiation, produced during operation of a reactor, is not the only hazard confronting nuclear power plant service personnel. Equally hazardous are radioactive gases, vapors and aerosols formed while the plant is in operation, which contaminate the atmosphere in the reactor and cooling system spaces. The inadequacy of proper precautionary measures can lead to overexposure of personnel in these spaces.

Let us examine possible reasons why activity penetrates the atmosphere of spaces in reactor plants.

During the operation of a power plant, the airtightness of connections in the primary loop (welded seams, valves, etc.) can be disrupted, resulting in contamination of the air by radioactive substances in the coolant.

In addition to radioactive substances resulting from activation of the coolant nuclei and its impurities, fission fragments can also penetrate the cooling system loop, together with the products of their radioactive transformation. The most dangerous of these are the gaseous and volatile substances, such as inert gases, iodine, etc. A number of gases produced during fission and decay of fission products are listed in Table 57.

Another source of gas activity is activation of the air wherever there is intensive neutron flux (for example, a layer of air serving as a heat insulator for a reactor). A number of isotopes in the atmosphere have large activation cross-sections. For example, argon - which comprises almost 1% of the atmosphere - has a thermal neutron activation cross-section of 1 barn and forms γ-active argon-41, while the nitrogen isotope N^{15} (nitrogen content of the atmosphere is 0.365%) absorbs thermal neutrons with a cross-section of 1.78 barns and forms the short-lived isotope N^{16} ($T_{1/2}$ = 7.35 sec). Possible fallout of aerosols and radioactive dust on clothing, shoes and various parts of the body must also be taken into account. If the appropriate precautionary measures are not observed, this can lead to overexposure of personnel.

This is precisely why air ejected from the reactor compartment - as well as water from the primary coolant loop, stored in special tanks aboard ship - can pose a danger. We must consider not only the possibility of an immediate effect on crew members or passengers, but also the danger of contaminating the sea water and surrounding atmosphere.

Table 57

A few characteristics [illegible] fission products

Isotope	Half-life	Fission product yield, %
Kr^{85}	9.4 yrs.	1.3
Kr^{87}	75 min.	2.8
Kr^{88}	3 hrs.	3.47
J^{131}	8 days	3.3
J^{132}	2.4 hrs.	3.76
J^{133}	22 hrs.	4.9
J^{135}	6.7 hrs.	5.9
Xe^{133}	5.3 days	4.9
Xe^{135}	9.2 hrs.	5.9
Sr^{90}	20 yrs.	5.2
Cs^{137}	37 yrs.	6.2

All of these considerations clearly establish the need for special radiation safety requirements and their observance in designing biological shielding for nuclear power plants, taking into account specific features of the ship, such as:

First of all, nuclear reactors, operating for a long period of time extending from several months to several years, and components of the reactor cooling system are located fairly close to living quarters and service spaces.

Secondly, the entire crew is aboard ship throughout the entire voyage.

Thirdly, during operation of the nuclear power plant the need may arise to undertake repair work and deactivation under navigational conditions.

Fourthly, during power plant operation the recurring problem of collection and disposal of resultant radioactive waste must be solved.

Finally, an important feature of a marine reactor plant is the need for periodic recharging of the reactors. This consists of removing the spent core (which, as already noted, is a strong source of ionizing radiation), charging a new core, and replacing a number of assemblies and individual units of the reactor compartment equipment - all of which are sources of radiation.

A radiation safety system, based on an analysis of possible sources of radiation from a nuclear power plant and taking into account specific features of the ship, has been devised. It includes a series of hygienic measures based on current recommendations relative to the maximum permissible radiation levels a body can be exposed to, as well as concentrations of radioactive substances in the water and atmosphere. In the final analysis there must be complete safety for personnel aboard ship and no contamination of sea water by radioactive wastes. Safety requirements have a bearing on the location of ship spaces. Sec. 63 is devoted to this problem.

63. Fundamentals of Space Arrangement and Nature of Hygienic Measures Aboard Nuclear-Powered Ships

The arrangement of spaces aboard nuclear-powered ships is determined by the need to keep the power plant sufficiently small, light and inexpensive as possible, while at the same time providing for adequate radiation safety. Optimum weight and size of a nuclear power plant can be obtained through compact arrangement of radioactive equipment in the reactor compartment, and also by placing spaces with sufficiently high permissible radiation levels near the vessel housing this equipment.

Various tanks, storerooms, vessels containing chemical fuel and other auxiliary spaces should be placed near the reactor compartment, so that they can serve as shielding elements, thereby reducing the weight of special shielding.

In selecting the amount of flux permissible in various spaces, we must consider the fact that service personnel spend differing amounts of time in these spaces in the course of a day.

A ship's spaces may be divided into the following four categories, depending upon the amount of time personnel spend in each:

1) Living quarters, where crew members might spend 24 hrs. a day (cabins, crew's quarters, ship's hospital, etc.).

2) Service spaces, where personnel spend an average of 8 hrs. a day (spaces containing machinery control points, etc.).

3) Partial service spaces, where personnel spend less than 8 hrs. a day (areas periodically visited, containing various types of equipment not requiring constant supervision, as well as corridors, ladders, etc.).

4) Nonservice spaces, which personnel do not enter at all during the entire operation of the power plant (compartments containing automatic equipment requiring no maintenance during power operation of the reactor).

Nuclear power plant shielding should be of such a nature that personnel will not be exposed to more than 0.1 rem/week, irrespective of when this dose is acquired (see Sanitary Regulations). Consequently, the less time spent in a given space during a 24-hour period, the greater the permissible level of radiation there. Permissible levels of radiation in nonservice spaces are established on the basis of permissible levels of equipment activation: the level of activated radiation must not exceed the level permitted to contaminate the space when the reactor is shut down for repair.

In arranging a ship's departments into compartments, nonservice spaces should be placed right next to the reactor compartment. Next come partial service spaces, then, finally, living quarters.

Weight reduction resulting from such an arrangement is possible because even though the radiation level outside the containment vessel usually exceeds the permissible biological dosage for the human body, it constitutes no hazard for chemical fuel reserves and other supplies. It should be noted that on the submarine NAUTILUS a similar arrangement of diesel fuel made possible their use as a shielding element.

In the majority of cases the turbine assemblies of atomic power plants do not have any significant bearing on the disposition of equipment. However, when single-loop gas and boiling-water reactors are used, due to the possibility of activity special features are taken into account in locating the turbine assembly. The presence of activity prevents the placement of control centers in these spaces, special ventilation is required, etc. There have been indications in the press that in the case of a boiling-water reactor the turbine assembly of the power plant must be biologically shielded in an air-tight space.

Considering the fact that biological shielding always contains a significant quantity of metal structures, it is recommended that they be placed so that they can contribute to the over-all strength of the hull, thereby making possible a decrease in the over-all weight of the ship.

Let us now turn our attention to the nature of measures taken on nuclear-powered ships to satisfy the hygienic requirements outlined in the preceding paragraph.

The reactors and their radioactive equipment are placed in a separate compartment or containment vessel, hermetically isolated from the ship's other spaces. In addition, a biological shield is placed between the sources of radiation in the reactor compartment and adjoining spaces. This biological shielding is thick enough to decrease to permissible limits the level of radiation to which personnel in these spaces are subjected. The reactors and reactor compartment equipment must be automated and remotely controlled to the extent possible. Time spent by maintenance personnel in the compartment is reduced to a minimum. To prevent the possible spread of activated aerosol and gas throughout the ship, an independent ventilation system must be installed in the reactor compartment (containment vessel), providing the necessary rapid air circulation and assuring that air outflow exceeds inflow, which in turn produces some discharge in the airtight reactor space. Before being dispersed into the atmosphere, the air circulated from the reactor compartment is cleaned with aerosol filters. It would be advisable to disperse the air as far as possible from the service spaces. For example, on the atomic icebreaker LENIN, air from the reactor compartment is discharged through the main mast, 20 m above the upper deck.

Before entering and after leaving the reactor compartment, personnel must first pass through a contamination control station, containing dressing rooms, showers, radiation monitoring stations and locker rooms where special clothing is kept. Entry into the reactor compartment is permitted only when special clothing is worn. This clothing is kept in the "contaminated" dressing room of the contamination control station. If activated aerosol is detected in the compartment, personnel are outfitted with special pneumatic suits with an uncontaminated pressurized air supply (for example, the LG-1 or LG-2, which are described elsewhere in a book).

Upon leaving the compartment, personnel and special clothing are subjected to radiation monitoring. If found to be contaminated, personnel are given medical treatment. Radiation monitoring is also repeated. Thus the contamination control stations divide the ship into two areas: contaminated and uncontaminated, thereby preventing dispersal of activity throughout the ship.

A laundry, equipped with special washing machines, is provided to wash contaminated clothing. The water used in these machines - like all other activated water in the reactor cooling system, shielding, etc. - is collected in special storage tanks usually located beneath the reactor compartment. The storage tank for highly activated water is properly shielded.

Activated water is stored for a while in tanks in order to decay short-lived activity. After it settles, the highly activated water is filter cleaned and diluted. Then the decontaminated and diluted water is reloaded onto a depot ship or thrown overboard. In the latter case water activity must not exceed the designated tolerance level. This level is selected in order to avoid injury to marine flora and fauna. Thus on the icebreaker LENIN the activity of disposed water does not exceed 5.10^{-9} curies/liter. The activated water is disposed of in specially designated areas.

In utilizing power generated by a nuclear reactor, special precautionary measures are taken for everyday needs. For example, on the atomic icebreaker LENIN, a third loop is used to heat spaces, with little likelihood of activity contaminating this loop.

A radiation monitoring system is being developed to survey radiation levels to which personnel are exposed, as well as activity scattering throughout the ship's spaces.

The stationary and movable instruments comprising this system make it possible to monitor radiation levels in various parts of the ship, air activity in spaces and in the ventilation system, and contamination of surfaces and process water with radioactive substances. Personal monitoring of service personnel is also performed. Stationary dosimeter instrument scales must be mounted on the control panel, where a health physicist is always on duty. In addition, the radiation monitoring system must include a sound and light signalling system in reactor compartment spaces, which is switched on whenever ionizing radiation exceeds tolerance levels, or whenever the air is contaminated.

Finally, of great importance in maintaining radiation safety aboard an atomic-powered ship is the training of personnel, which includes familiarization with and strict observance of special instructions. Thus the basic precautions which will insure proper radiation hygiene are as follows:

1) Shielding of reactors and other radioactive equipment;

2) Isolation of the reactor compartment, establishment of an independent ventilation system, and creation of "limited access" and "unlimited access" areas (in order to get from one to the other, one must pass through contamination control stations);

3) Provision for a radiation control system, to include all types of radiation effects enumerated above;

4) Establishment of a system to dispose of activated water and air, preventing contamination of sea water beyond the tolerance level, and preventing fallout of activated air into an inhabited area;

5) A system that will assure safe utilization of energy for everyday needs; and

6) Appropriate training of personnel and strict supervision to make sure they carry out special instructions.

We might illustrate the above using the example of the atomic icebreaker LENIN and the passenger-cargo ship SAVANNAH.

The reactor plant of the icebreaker is located in an airtight space - the "central" compartment, equipped with independent ventilation, which causes discharging. Before entering and after leaving the reactor compartment, personnel must pass through a contamination control station. The reactor compartment spaces are not under constant guard.

Only service spaces are adjacent to the central compartment: the turbine room aft and auxiliary machinery space forward; store rooms and electric control panel spaces are located along the sides, with the pump and piping space down below; ventilator and loading shaft are located above the reactor compartment. Radiation levels in continuously guarded areas do not exceed 0.3 of the maximum tolerance level. In rest areas the radiation level is equal to the natural radioactive background.

The icebreaker's radiation monitoring system includes signalling and radiation recording instruments in all spaces adjoining the central compartment. Light and sound signal units can be found wherever sensors are placed, as well as at the entrance to "limited access' areas, and are hooked up with the central radiation monitoring room, where a health physicist is always on duty. When the signal is given, everybody must immediately leave the contaminated space. Entry into this space can be made only through special permission of the duty health physicist.

In addition to the so-called biological dosimetry system described above there is also an equipment monitoring system on the icebreaker to monitor leakage of the coolant. This system consists of a group of radiometers, with sensors placed wherever leakage might occur, and wherever measurements are most effective (at the filter cooler outlets in the auxiliary loop in turbine condensers).

There is also a system to monitor the primary loop coolant in case the airtightness of the fuel elements is impaired and in case there is fission-fragment activity in the loop. This monitoring is accomplished using a γ-radiometer in the primary loop by-pass and through periodic analysis of bidistillate samples.

A warning signal is given whenever the activity level of the coolant exceeds 0.01 curies/liter.

The storage and disposal of activated water is accomplished as follows: Slightly activated water (with an activity of less than 10^{-6} curies/liter) is poured into a 3 m^3 tank after the spaces have been washed down and water and clothes from the contamination control station and laundry have been decontaminated. After being stored in the tank awhile and diluted, the water is thrown overboard. Highly activated water is poured into a 10 m^3 tank (shielded by a 28-cm iron plate), from which it can be thrown overboard after special decontamination and dilution.

The activation level of the air is kept below 3.10^{-11} curies/liter in the spaces and 10^{-8} to 10^{-9} curies/liter in the ventilator ducts with the aid of a special ventilator system. Air for shipboard needs is funneled through the base of the mast, where its activity does not exceed 10^{-10} curies/liter, which is the maximum tolerance level.

Finally, personal radiation safety precautions also include periodic medical examinations for the crew (in which the radioactive isotope J^{131} content of the thyroid gland is measured), measurement of cumulative dosage received by each crew member (using pocket dosimeters), radiation monitoring of various parts of the body, clothing, etc. upon leaving the central compartment.

Radiation monitoring aboard the passenger-cargo ship SAVANNAH consists of two operations: monitoring of equipment and radiation safety.

Equipment monitoring involves monitoring the level of radiation and activation at reactor monitoring points, enabling us to discover in advance many operational abnormalities.

A radiation safety system continuously monitors radiation levels and observes deviations from their normal values. Monitoring is done with the aid of 12 dosimeters installed in various spaces. Self-recorders continuously record instrument readings.

The possibility of entry into the protective envelope can be determined with the aid of radiation monitoring instruments, mounted near the envelope hatch (see Chapter XIII). In addition, each crew member entering the envelope carries a pocket dosimeter to determine radiation dosage picked up during the work period.

In addition to the stationary radiation monitoring instruments, there are also a number of portable instruments aboard ship for special measurements. These instruments are used to check the effectiveness of decontamination and to measure activity during repair work.

The radioactive waste disposal system aboard the passenger-cargo ship SAVANNAH provides for drainage of all possible radioactive leakage from the reactor loop. Water appearing on the floor of the reactor compartment can be pumped into a storage tank for waste materials. The radioactive waste elimination system consists of two pumps, slide-valve bolts, piping, a collection tank and four storage tanks. Total volume of the tanks is 38.4 m^3, which exceeds by 80% the maximum operating leakage through drainage for an operating period of about 100 days. Liquid samples can be taken from each tank for analysis at any time. If the activity level of the samples is sufficiently low, the liquid is pumped into special tanks. Liquid wastes cannot be thrown into the sea, except under unusual circumstances as indicated by the Navy Department and the Atomic Energy Commission. A special barge has been designed for transporting liquid wastes.

A large quantity of radioactive gases accumulates in the reactor ventilation system piping. Here the gases are diluted with air and released into the atmosphere through the mast, with the aid of a ventilator. The activity level of the gases is continuously monitored.

Under normal conditions, the reactor ventilation system operates continuously. The space between the protective envelope and the secondary shielding is also ventilated. Moreover, even though the gas may not be activated, an activity measuring instrument is installed to insure complete safety.

All of the gases are passed through a filter to eliminate activated particles before being released through the mast.

The air in the protective envelope is periodically ventilated and cleansed of radioactive particles. During normal reactor operation, the only radioactive gas inside the envelope is Ar^{41}. Fission products cannot penetrate the airtight envelope during normal reactor operation. Nevertheless, samples are analyzed for fission-fragment activity before the air circulation begins.

64. Principles of Decontamination

During the operation of a marine reactor, clothing and shoes - as well as decks and ship's equipment - can become contaminated with radioactive substances (from this point of view, recharging nuclear fuel poses a special hazard). The disposition of such contaminants is considerably complicated by the fact that radioactive substances enter into formation of a chemical compound with the material and are adsorbed into its surface layer. Therefore, it would be more practical to use materials which are chemically stable with respect to acids, alkalis and organic solvents, and also possess the lowest adsorbability. Adsorbability, for our purposes here, can be determined as a ratio of activity remaining after washing of the surface of the material to initial activity.

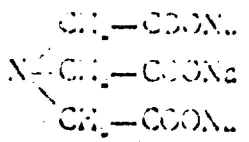
Many plastics have low adsorbability (1% in the case of polyethylene, for example), as do surfaces coated with special paints. In this regard, stainless steel has the best properties of all construction materials.

Concrete and lead, frequently used for shielding, possess high adsorbability (concrete retains practically all of its induced activity, and lead about 75%). This is also one of the reasons, incidentally, why it is necessary to coat lead with stainless steel.

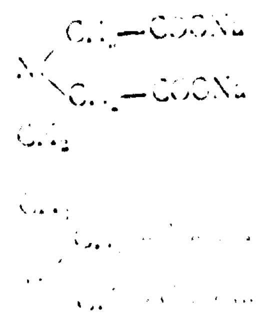
In addition to washing radioactive contaminants with water or special solvents, decontamination is also accomplished by removing the surface layer of the substance through scrubbing, scouring, sandblasting, metal shot blasting, or the use of solvents. However, the trouble with these methods is that the outer layer of the substance is damaged, thereby increasing its adsorbability.

There are indications that radioactive contaminants can be eliminated from micropores in the surface through ultrasonic treatment.

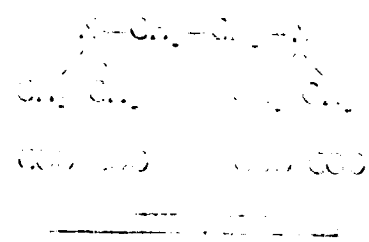
If the surfaces are contaminated with fission-fragment activity, the use of complexing reagents is recommended. For example, sodium nitrilotriacetate:



or sodium ethylenediaminetetraacetate:



These compounds form, with bivalent, trivalent, quadrivalent and hexavalent metals, stable complexes of the type:



The effectiveness of decontamination methods is determined by the ratio of surface activity of the material after treatment to activity before treatment (but after washing with water).

Various recommendations have been made for deactivation of the most widely used construction materials. For example, one method of decontaminating stainless steel consists of treating it (after careful washing with water) with a hot 10% nitric acid solution, followed by treatment with hydrochloric acid. It is much more difficult to decontaminate steel and lead, and completely impossible to decontaminate concrete.

It should also be noted that repeated decontamination is always less effective than the first treatment.

Several methods of treating the surfaces of various materials during decontamination are shown in Table 58.

Methods of Treating Surfaces During Decontamination

Material	Decontamination Treatment Method
Stainless steel	Scrubbing with nitric acid at varying concentrations and temperatures, then washing with soda
Low-carbon steel	Scrubbing with hard brushes in a 10% citric acid solution and a 5% soap powder solution, followed by washing in water
Lead	Washing in hydrochloric acid, then washing again in a large volume of water
Brass	Rubbing with acetone; polishing with a rag, wetted in the ammonium salt of acetic acid and sodium phosphate, dried with absorbent tissue. Washing in acids is recommended.
Aluminum	Washing in a 10% nitric acid solution, using a brush
Glass	Treatment with a 60% nitric acid solution over a period of days, then treatment with a chromium sulfate solution
Plastics	Washing in acetone, sodium ethylenediaminetetraacetate, ammonium citrate. Polish with a rag
Concrete	Scraping with a hard brush and abrasive powder; washing with water, soap, citric acid and sodium phosphate. Treatment with a metal shot blasting machine or sandblasting machine
Wood	Treatment with a metal shot or sandblasting machine. Removal of surface layer using woodworking instruments or an autogenous burner. Washing in a 1% solution of light soap in a sodium hexametaphosphate mixture
Instruments	Boiling in a 10% acetic acid and 5% soap solution, washing with water
Asphalt, brick	Washing in foaming agents
Linoleum	Washing in a hot trisodium phosphate solution, removal of the surface layer with a wire brush

65. Recharging Nuclear Fuel

After the nuclear power plant has finished its run, the reactor core must be changed. The core recharging process is considerably complicated by two factors. First, the fission products that have accumulated in the fuel elements are strong sources of γ-radiation. Therefore, the nuclear fuel must be changed, using special devices which provide biological shielding for personnel during the recharging. Secondly, radioactive decay of fission fragments results in the liberation of a considerable quantity of heat, which necessitates cooling of the spent core. The amount of residual heat liberation is determined basically by the length of time the reactor has been in operation and the type of reactor.

Figure 119 graphically illustrates the dependence of residual heat liberation on time elapsed from the moment the reactor is shut down.

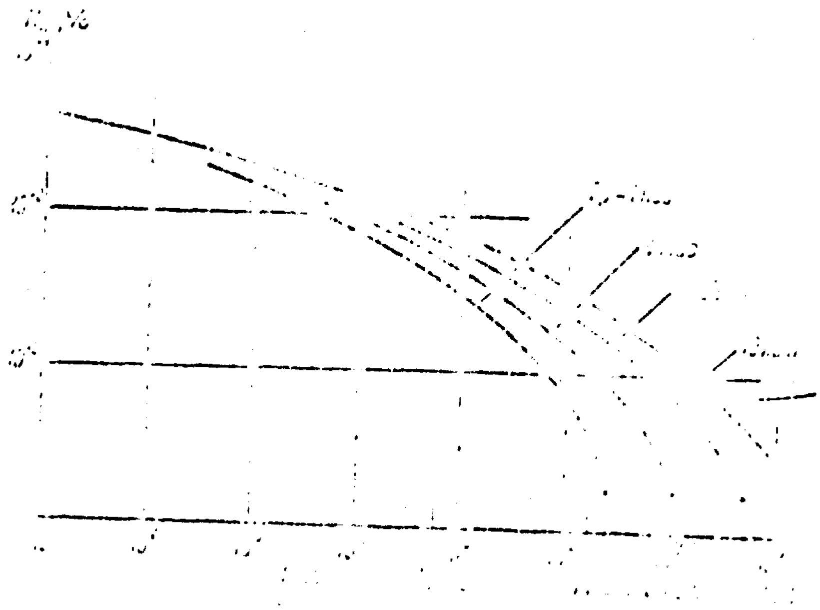


Fig. 119. Dependence of amount of residual heat liberation in the core on time elapsed after the chain reaction t_s is stopped (T_0 = duration of previous reactor operation).

a) T_0 = 1 week; b) 1 month; c) 1 year; d) 10 years; e) 1 hour; f) 1 day; g) 1 month; h) 3 months; i) t, sec.

Recharging the spent core of a marine reactor can be accomplished either by placing the ship in a specially equipped dock or floating it in calm water, using harbor facilities. After shutdown of the reactor, forced cooling of the core is continued until the level of residual heat liberation permits placing of the core in an uncooled transport container for a short while. The core is delivered to a special tank in this container.

There are various possible recharging methods, such as: core recharging, in which the entire core is transported from the reactor vessel to a tank in a protective container of the proper dimensions; recharging of individual fuel elements or assemblies; and recharging the core in individual parts. Of course, the size and thickness of the protective containers (recharging containers) vary according to the recharging method. Special attention should be given to proper functioning of transport equipment, since any incident - even a mere holding up of the container during recharging - can lead to very serious consequences, including overexposure of service personnel and alteration of the structure of the container as a result of heat liberation.

Construction of the container depends on the recharging method and the shape and weight of the recharged core components. Therefore, in each specific case the problem of designing recharging devices is solved accordingly.

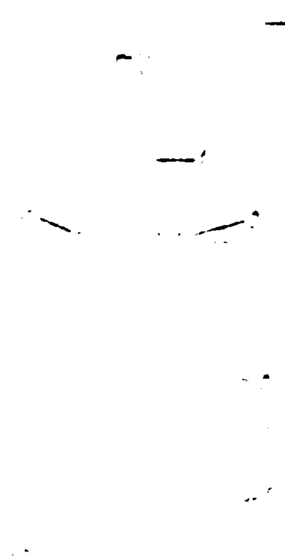


Fig. 120. Container for transporting spent fuel elements.

1) Hydraulic drive; 2) water outlet; 3) Device for gripping and removing fuel elements; 4) Lead shielding; 5) Position of the fuel assembly; 6) Bottom lead valve; 7) Channel; 8) Position pins; 9) Cooling water; 10) Water inlet.

Ordinarily, the container consists of a thick-walled steel or lead cylinder (lead, of course, is not as malleable as a construction material, but if it is used the weight and dimensions of the container can be reduced). Figure 120 shows the design of a container for transporting spent fuel elements. Determination of the thickness of the container walls can be regarded as the problem of determining the dose at a point behind the shielding of the cylinder source. In determining the strength of the sources, we only have to calculate the γ-radiation of fission products (see Chapter IV). The necessary attenuation multiplicity factor is determined from the fact that the level of

γ-radiation behind the container must not exceed a level creating the maximum permissible dose for the period of time the core (or fuel element) remains in the container, i.e., the time during which personnel are subjected to γ -radiation effects from the core, which is attenuated by the walls of the container. Thus the maximum tolerable dosage of γ-radiation of power E D_γ (E, t), obtained during charging time t hours, is:

$$D_\gamma (E, t) = D_\gamma (E, 6 \text{ hours}) \frac{t}{6},$$

where D_γ (E, 6) is the maximum permissible dose during a 6-hour working day.

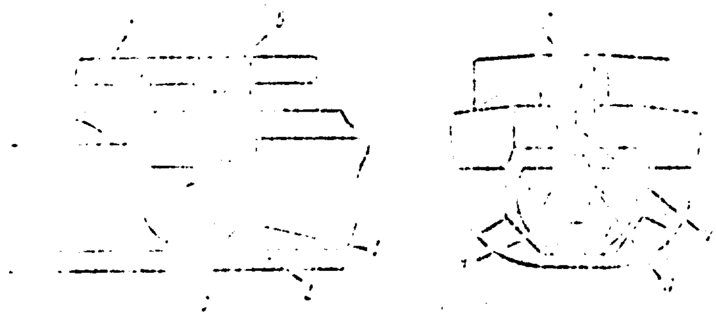


Fig. 121. Schematic drawing of nuclear fuel recharging for a nuclear power plant aboard a tanker.

1) Core; 2) Biological shielding; 3) Protective container; 4) Protective container cover; 5) Transport container; 6) Recharging device; 7) Shielding pit.

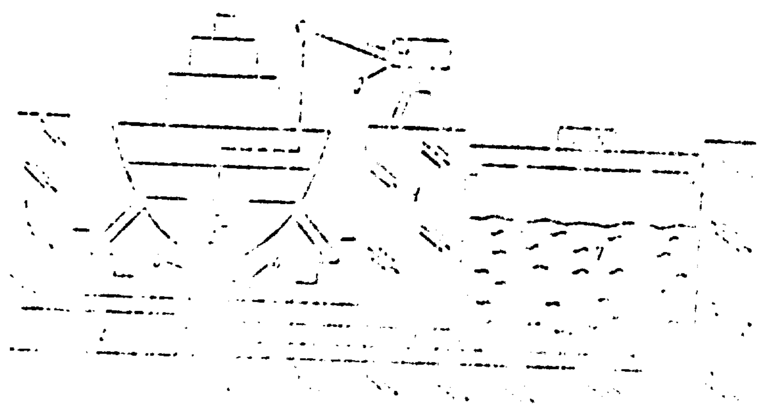


Fig. 122. Schematic drawing of the nuclear fuel unloading process, through the bottom of a ship.

1) Concrete dock; 2) Contaminated water treatment plant; 3) Keel blocks; 4) Caisson; 5) Channel for transporting spent fuel elements; 6) Spent fuel assemblies; 7) Cooling pond; 8) Bridge crane; 9) Crane for loading new fuel assemblies.